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Ciencia Tecnología y Futuro

LITHOLOGY AND FLUID SEISMIC DETERMINATION FOR THE ACAE AREA, PUERTO COLÓN OIL FIELD, COLOMBIA

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(Received 15 June 2005; Accepted 1 November 2005)

In this work, we applied enhanced geophysical techniques to detect new prospecting zones at the Puerto Colón oil field. The easier-to-produce hydrocarbons are currently being or have been extracted. In order to extract harder-to-produce hydrocarbons, we need to better define the Caballos formation characteristics.

We obtained an acceptable match between the rock-physics laboratory measurements and the petrophysical properties estimated through the use of seismic data.

We used well logs to guide the seismic measurements in the estimation of both porosity and gamma-ray response (from seismic attributes), and acoustic impedance (via seismic inversion), using a neural network approach.

We applied a probabilistic neural network (PNN) because of its particular characteristics of 1) mapping non linear relationships between seismic and well log data; 2) incrementing both accuracy and resolution when performing inversion, as compared to conventional inversion, and; 3) using a mathematical interpolation scheme not implemented as a black box.

Poisson and Vp/Vs ratio provide a means to discriminate between high and low reservoir-rock quality at the Caballos formation. Finally, we analyzed three angle gather stacks (0°-10°, 11°-20° and 21°-30°) through elastic inversion.

Keywords: *seismic attributes, seismic modeling, neural network, rockphysics, seismic inversion, reservoir geophysics, Colombia, Puerto Colon.*

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En este trabajo aplicamos técnicas geofísicas mejoradas para detectar nuevas zonas prospectivas en el campo petrolero Puerto Colón.

El petróleo fácil de producir esta siendo explotado y para poder extraer el petróleo difícil de extraer necesitamos definir sísmicamente mejor las características de la Formación Caballos.

Obtuvimos una estimación aceptable entre las medidas de laboratorio de física de rocas y las propiedades petrofísicas estimadas con los datos sísmicos. Se usaron registros de pozo para guiar el cálculo sísmico de porosidades, la respuesta del gamma-ray (a partir de atributos sísmicos) y la impedancia acústica (vía inversión sísmica) usando redes neuronales.

Se utilizó una red neuronal probabilística (PNN) debido a su particular característica de 1) mapear relaciones no lineales entre la sísmica y los registros de pozo; 2) incrementar tanto la precisión como la resolución cuando se realiza la inversión comparada con los métodos convencionales, y 3) el uso de un interpolador matemático que no esta implementado como una caja negra.

La relación de Poisson y Vp/Vs provee el medio para discriminar entre roca del yacimiento de buena y de baja calidad. Finalmente se analizan tres apilados parciales por ángulos (0°-10°, 11°-20° y 21°-30°) en la inversión elástica.

Palabras claves: *atributos sísmicos, modelamiento sísmico, redes neuronales, física de rocas, inversión sísmica, geofísica de yacimientos, Colombia, Puerto Colón.*

INTRODUCTION

In this study, the use of the following geophysical techniques will be examined.

Acoustic and elastic seismic inversion, with the purpose of matching model reflectivity from well logs to that contained in seismic data; acoustic inversion as acoustic impedance generation for the attribute analysis step and elastic inversion as a mean for Poisson and Vp/Vs ratio generation useful in reservoir quality discrimination.

Attributes analysis to predict petrophysical properties from seismic attributes.

Seismic modeling/fluid replacement modeling to create full offset synthetic gathers to analyze the impact of reservoir fluids in the seismic signature.

Spectral decomposition, to take into account frequency variations at reservoir level for amplitude/frequency analysis and generation of external seismic attributes. These attributes are used as input for the attribute analysis to predict petrophysical properties.

Puerto Colón Oil Field remarks are:

The geologic structure is an asymmetric anticline with approximately N-S strike, average dip of four degrees and inverse faulted on the east flank that controls oil accumulation (Figure 1).

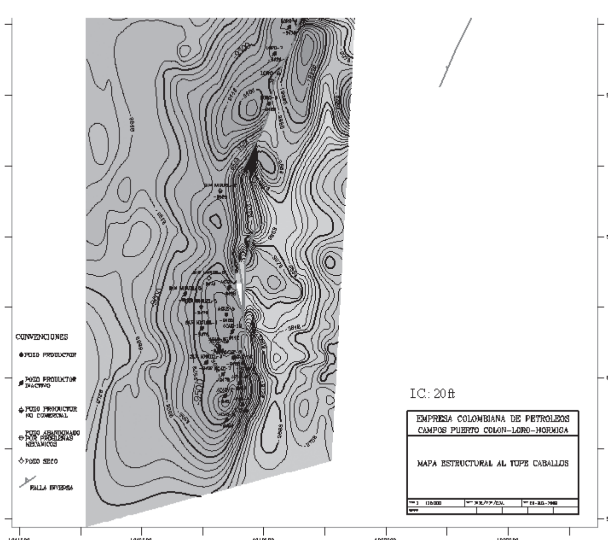

Figure 1. Structural map at the top of Caballos formation (Peña *et al.,* 2000)

The original oil in place (OOIP), including the North Loro oil field, totals 319,2 million barrels (MB) with a recovery factor of 13% as of 2000. The oil is classified as black oil with 30,5 0API, GOR of 458 Scf/stb, a volumetric factor of ß0=1,27 bl/stb, density of 878 kg/m^3, and viscosity of 0,919 cp at reservoir conditions. The oil-water contact is tilted East and South East, -9570 feet depth East and -9750 feet South.

The reservoir at the Caballos Fm is sub saturated with permanent water drive; initial reservoir pressure was 4750 psi @ -9625' and currently is 4350 psi; bubble pressure is 1600 psi. Due to the difference between the bubble pressure and the reservoir pressure, the GOR and volumetric factor have not changed after 30 years of production, and no free gas cap has been developed (Acevedo, 2002). Properties of the reservoir water are: specific gravity of 1,02, salinity between 10,000-20,000 ppm, and resistivity of 0,25 ohm-m.

AVAILABLE DATA AND METHODOLOGY

The following datasets and reports from the study area were available:

Seismic data available for this study is a subset (pre- and post-stack data) corresponding to the Acae area, with a total of 31 Km^2; the total surface covered by the seismic survey was 220 Km^2 with 100 Km^2 full-fold. The sample rate for the Acae subset is four milliseconds.

Eleven well logs.

Formation tops and interpreted seismic horizons.

ECOPETROL´s S.A. internal reports on Reservoir evaluation, Rockphysics, Seismic inversion and AVO analysis performed previously.

Lithology assessment methods consist of:

Conventional wavelet analysis to estimate the seismic resolution 'tuning analysis' at the reservoir level, taking into account the seismic sample rate and the wavelet used to match the well logs with the seismic data, and for the elastic seismic inversion.

Applying a neural network (nn) technique for both the acoustic inversion and the seismic attribute analysis to predict the petrophysical properties porosity, Poisson's ratio and the Gamma-Ray log response. The non-linear approximation of nn to better match the rock properties is the goal.

Elastic inversion including elastic impedance normalization (Whitcombe *et al*., 2002) to calculate Vp/Vs, Poisson Ratio, and Lambda/Mu parameters.

Application of Instantaneous Spectral Analysis (ISA), a spectral decomposition technique that accounts for frequency variations in the seismic signature, examination of its effect on resolution at the reservoir level, amplitude analysis with frequency and generation of frequency cubes used as seismic attributes in the petrophysical prediction step. ISA is also useful in gas detection, improved visualization of stratigraphic features, estimation of thickness for thin beds, noise suppression, improved spectral balancing, and direct hydrocarbon indication (Castagna *et al*., 2003).

The methodology for the seismic fluid assessment includes a fluid replacement modeling (using Zoeppritz and Gassman's Equations) and the angle gather stack. This angle gathers stack can be generated both from synthetic gathers and the seismic survey acquired cdp gathers.

The application of these techniques in the Acae area is complementary to the ones used in the previous studies performed.

APPLICATION OF TECHNIQUES AND RESULTS

The application of the techniques is focused on the reservoir level of the Caballos Fm. As required by the method, additional information is taken beyond the Caballos Fm thickness range.

The "lithology assessment" includes an elastic inversion to discriminate poor-quality from good-quality reservoir rock at Caballos, based on laboratory results (Petrophysical Consulting Inc., 2000) and the use of seismic attributes to extrapolate using seismic traces, significative rock properties for this reservoir such as porosity and gamma-ray response.

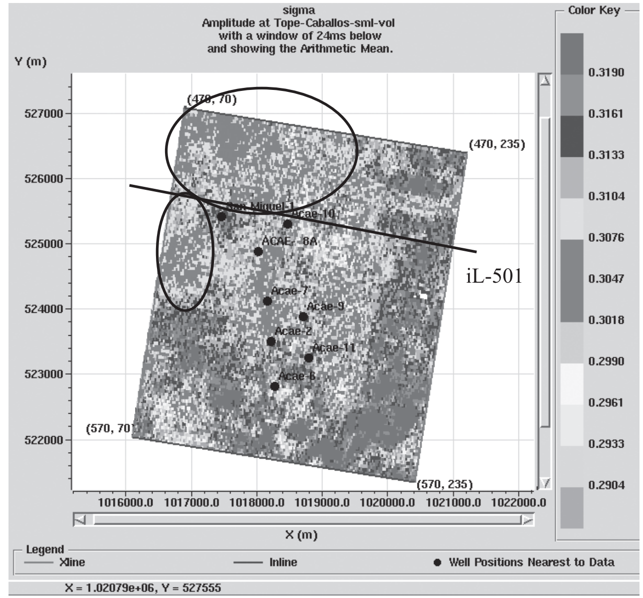

Figure 2. Shows the Poisson ratio from elastic inversion calculation at the upper Caballos formation (arithmetic mean in a 24 ms window below top). Black ovals highlight good quality rock

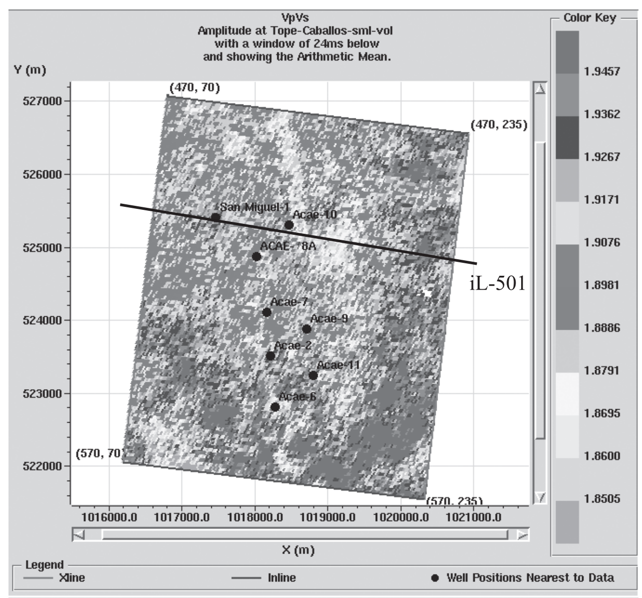

Figure 3. Shows Vp/Vs ratio from elastic inversion calculation at the upper Caballos formation (arithmetic mean in a 24 ms window below top)

The Poisson's ratio and Vp/Vs ratio results from applying the Mr. Portniaguine's elastic inversion algorithm are shown in map view and for the in-line 501, in Figures 2 to 4 for the Upper Caballos.

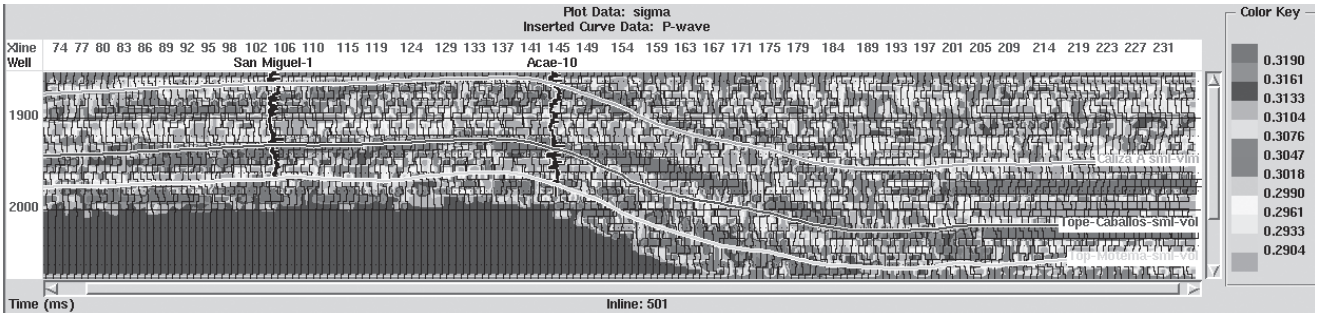

Figure 4. Shows the Poisson ratio from elastic inversion calculation. Inline 501 shows wells Acae10 and San-Miguel1

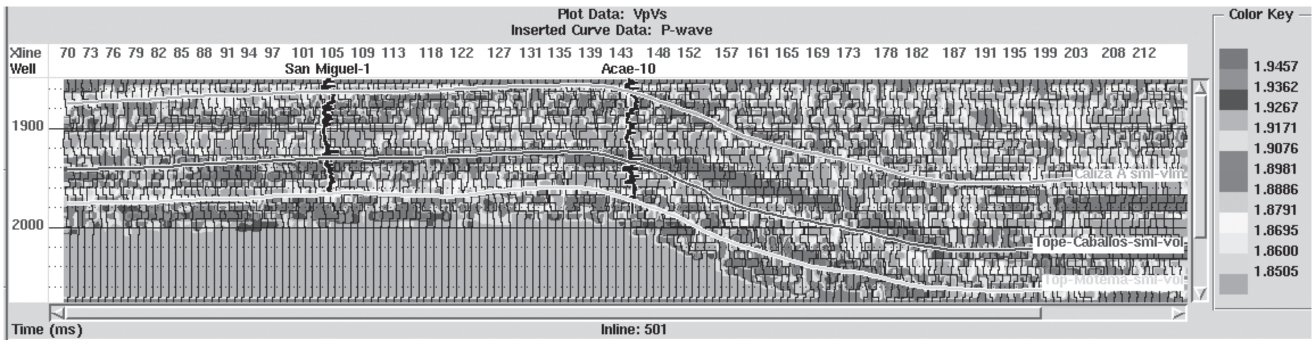

Figure 5. Shows the Vp/Vs ratio from elastic inversion calculation. Inline 501 shows wells Acae10 and San-Miguel1

According to the rock-physics report, high values of either Poisson's ratio or Vp/Vs ratio correlate with low quality reservoir rock while low values (Poisson's and Vp/Vs) correlate with good quality reservoir rock. GOR in the reservoir has no change in the last 30 years, so fluids behavior have remain constant.

We observe low Poisson's and low Vp/Vs values at the Acae-10 well (Figure 4) and high Poisson's and Vp/Vs values at the San Miguel-1 well (Figure 5).

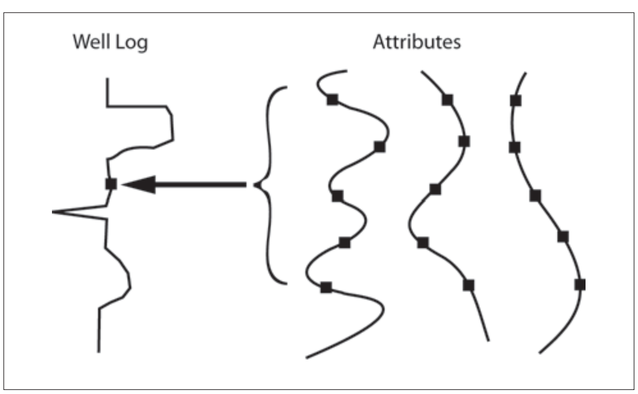

Figure 6. Shows a five-point convolutional operator relating the seismic attributes to the target log (Hampson *et al.*, 2001)

These values match the reservoir rock quality in both wells, with the San Miguel-1 well having a higher clay content than the Acae-10 well.

Generating a porosity volume from seismic attributes using a Probabilistic Neutral Network (PNN):

In the training step (PNN), the difference in frequency between the well log and seismic data is handled through the use of a convolutional operator (Figure 6). We find a five point convolutional operator to be the best choice for the Acae area. A longer operator creates a noisier output while a shorter operator results in a lower correlation at the validation step.

We used six attributes (Table1) to achieve the maximum correlation, both in the training and validation steps for the Acae area, as shown in Figures 7 and 8. We trained neural network with wells Acae-5, Acae-6, Acae-8a, Acae-10, and Acae-11.

The six attributes were chosen through the use of a multi-linear stepwise regression approach (Hampson *et al.*, 2001). The stepwise regression is carried out as follows:

Table 1. Attributes used in the Acae area for porosity determination

Stepwise Step	Attribute
1	Cosine Instantaneous Phase
2	Near-stack
3	Filter 5/10-15/20
4	Integrated Absolute Amplitude
5	(Acoustic impedance cube)**2
6	1 / (Gamma Ray cube)

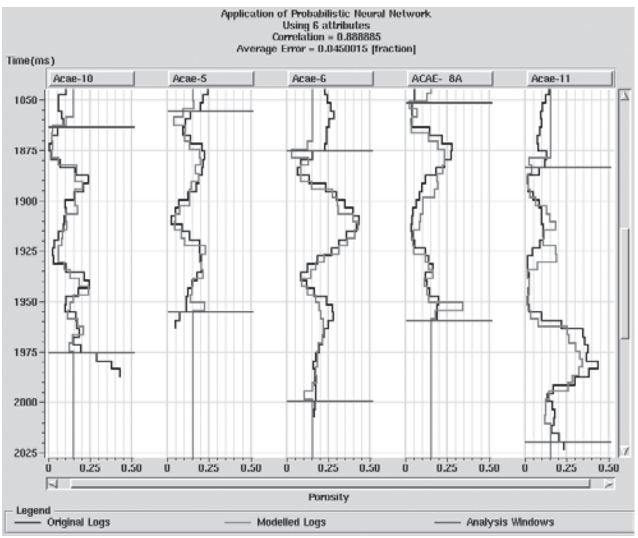

Figure 7. Correlation (0,88) in the training step. Black line is the original log, gray line is the modeled log

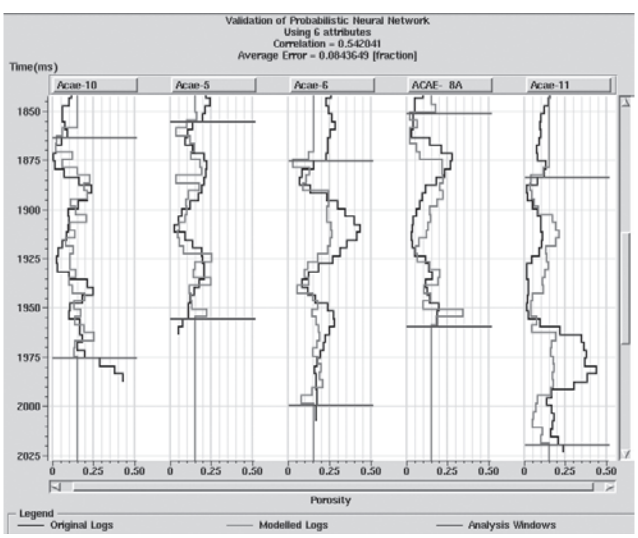

Figure 8. Correlation (0,56) in the validation step. Black line is the original log, and gray line is the modeled log

For example, from a list of n attributes this approach finds:

First, the single best attribute via exhaustive search (lowest prediction error).

Second, the best pair of attributes (lowest prediction error), assuming that the first member is attribute1, as found in the previous step.

Third, the best triplet of attributes (lowest prediction error), assuming that the first two members are attribute1 and attribute2 from the previous step, and so on until reaching n attributes. For this study n=10.

The porosity map view of the upper Caballos formation is shown in Figure 9, while the in-line 501 is shown in Figure 10.

The porosity values for the upper Caballos formation match the average values reported in the production reports and the rock-physics report (Petrophysical Consulting Inc., 2000, p.119).

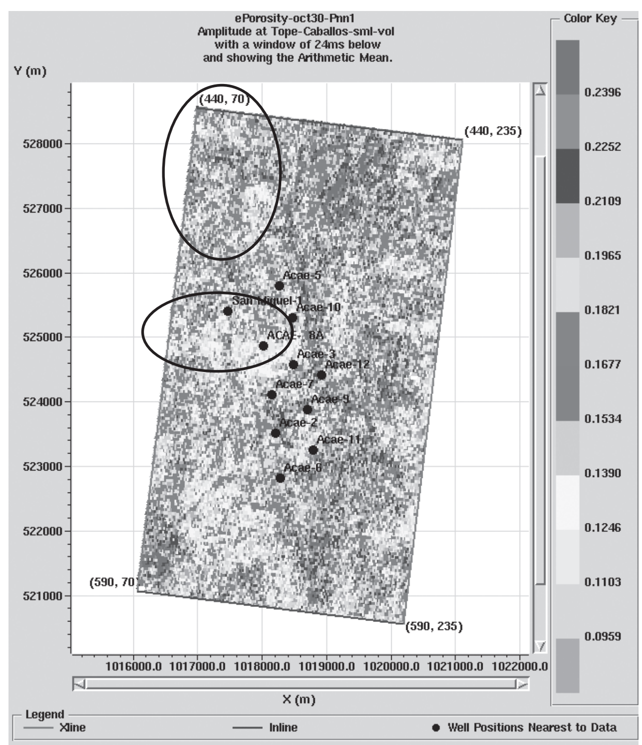

Figure 9. Shows the upper Caballos porosity estimation (24 ms window below the top –arithmetic mean) Black ovals highlight good porosity rock

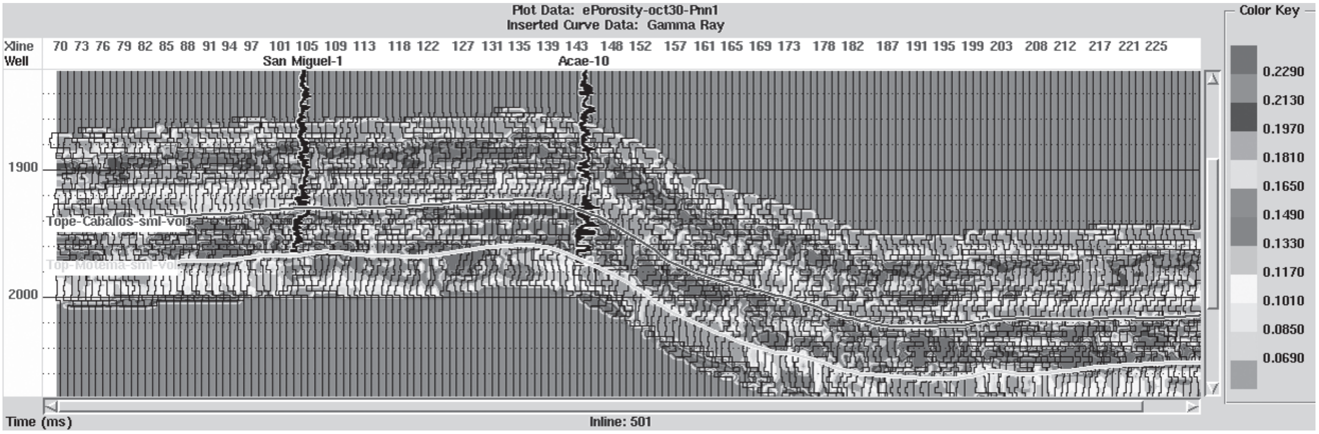

Figure 10. Shows the porosity estimation at Inline 501. Wells San Miguel1 and Acae10 are shown

The *fluid assessment* studies the reservoir fluid properties of the Caballos formation to check if they are seismically significant.

Fluid substitution using synthetic traces

The geometric parameters used in synthetic modeling were taken from the Acae 3D seismic survey design to model three synthetic cdp gathers for the cases of oil, brine and gas fluid filling the rock pore. Each synthetic gather is compared to the actual cdp gather at the well Acae-10 location for comparison. This well shows good development of the producing unit-4. The modeling was focused in a time window between 1924 ms to 2010 ms containing the Caballos formation interval and accounted for geometrical spreading, transmission losses, and array effects (6 inline geophones with 4 m spacing per receiver group).

Through the available range of angles used to model the synthetic seismic response along

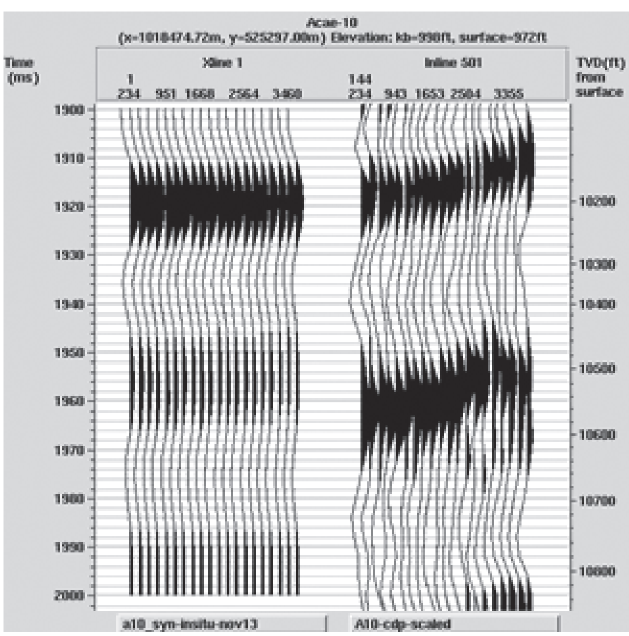

Figure 11. Shows the in-situ case –oil saturated with the synthetic gather on the left and actual gather on the right. The event of interest is located between 1,950 and 1,960 ms

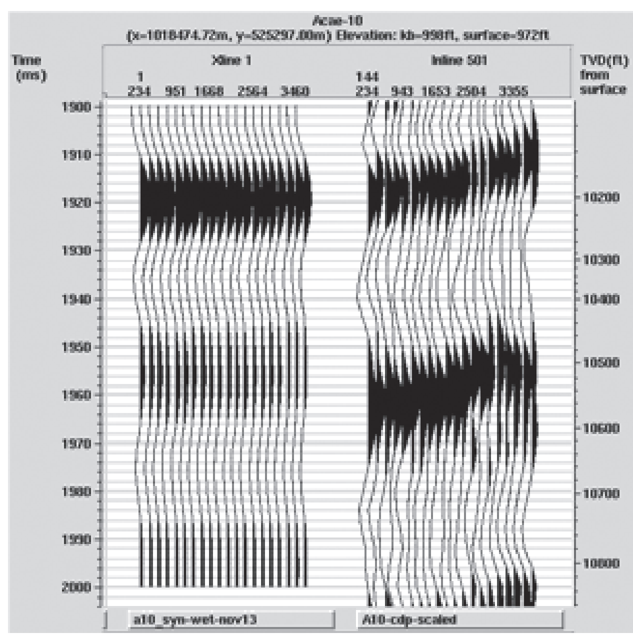

Figure 12. Shows the brine case –water saturated with the synthetic gather on the left and actual gather on the right. The event of interest is located between 1,950 and 1,960 ms

with the geometric parameters from the seismic acquisition design, the synthetic gathers are generated. Three synthetic gathers corresponding to the in-situ (oil saturated), brine and gas cases are modeled. Figures 11 to 13 show the synthetic gathers with the actual seismic gather added for comparison purposes.

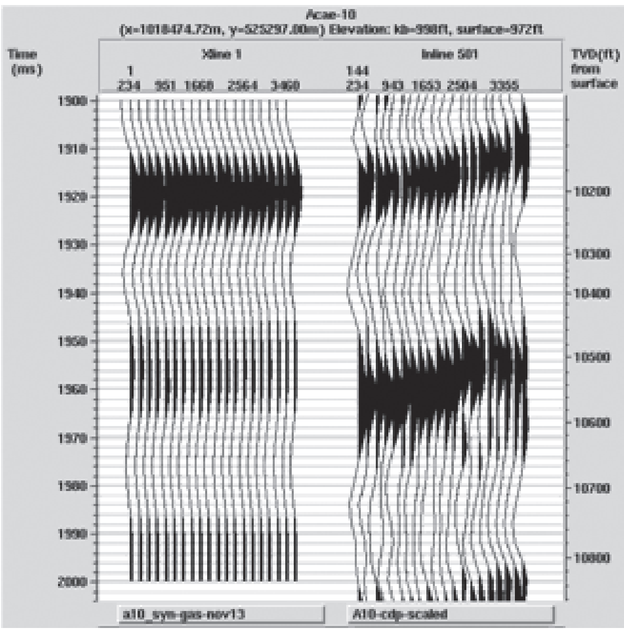

Figure 13. Shows the gas case –gas saturated with the synthetic gather on the left and actual gather on the right. The event of interest is located between 1,950 and 1,960 ms

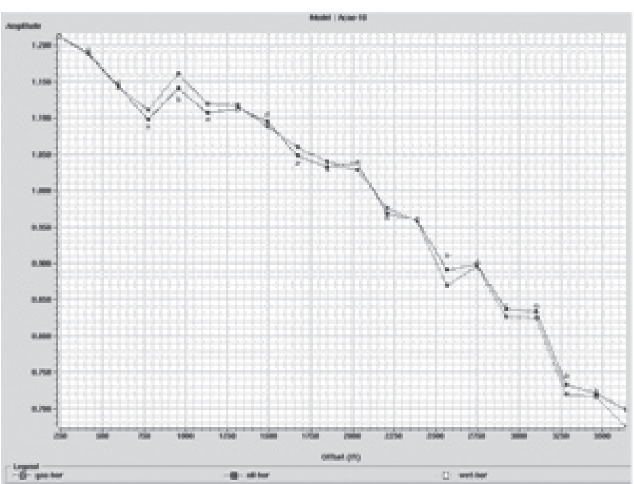

Figure 14. Normalized amplitude versus offset plot for the gas (upper line), oil (middle line), and brine (lower line) cases.

As shown in Figures 11, 12 and 13, the synthetic response is practically the same for the oil, brine and gas case. For quality control purposes, the event of interest was picked to show the amplitude differences between the three cases, as shown in Figure 14. The well log differences after performing fluid substitution is shown in Figure 15.

Several other AVO attributes were tested with the synthetic traces, and no seismic signature was obtained from these attributes when generating stacks, namely the following: the product (A*B) where A is the inter-

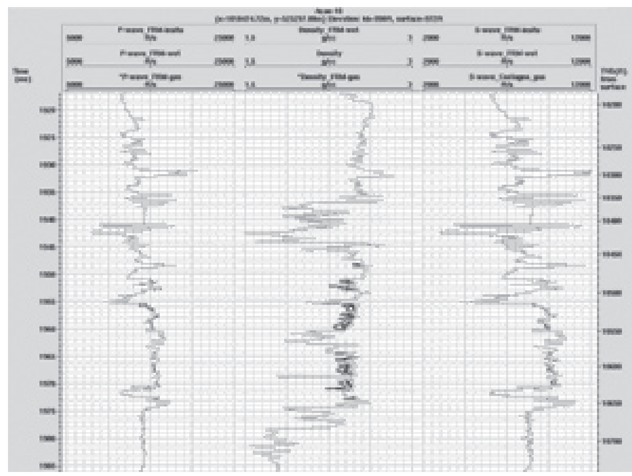

Figure 15. Mosaic showing the well logs after performing fluid substitution. Oil case (right line), wet case (center line), and gas case (left line).

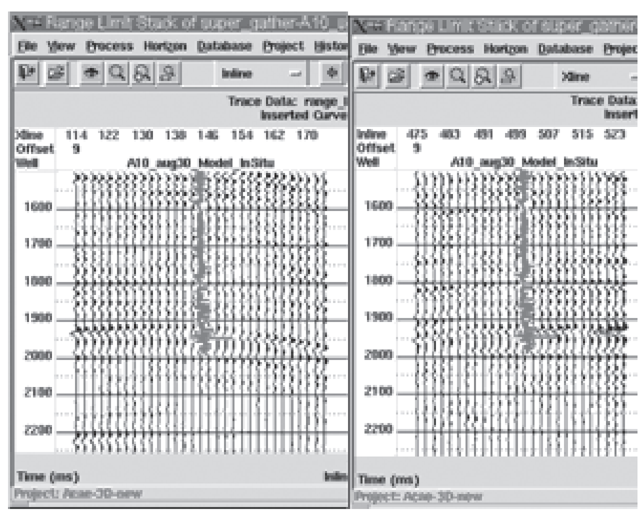

Figure 16. Shows a near angle stack (0°-18°) at well Acae-10 location with Inline 501 on the left, Xline 144 on the right

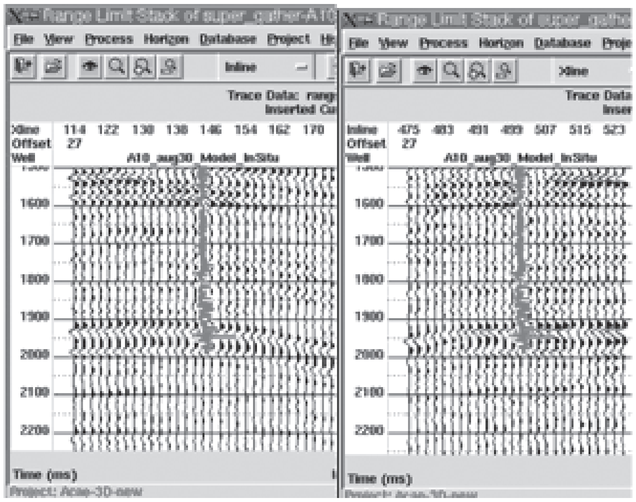

Figure 17. Shows a far angle stack (18°-36°) at well Acae-10 location with Inline 501 on the left, Xline 144 on the right

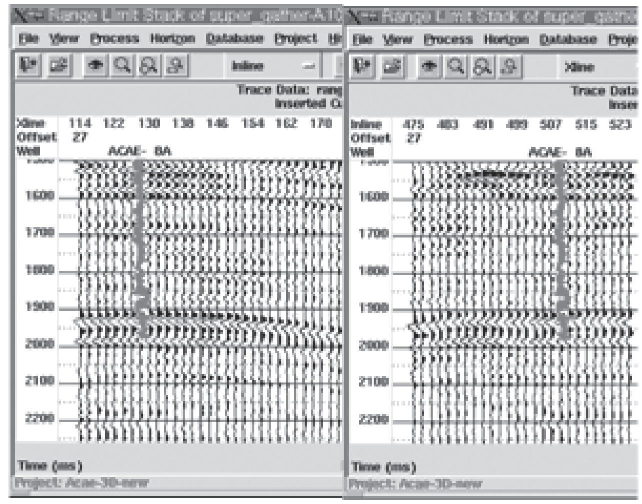

Figure 19. Shows a far angle stack (18°-36°) at well Acae-8a location with Inline 509 on the left, Xline 128 on the right

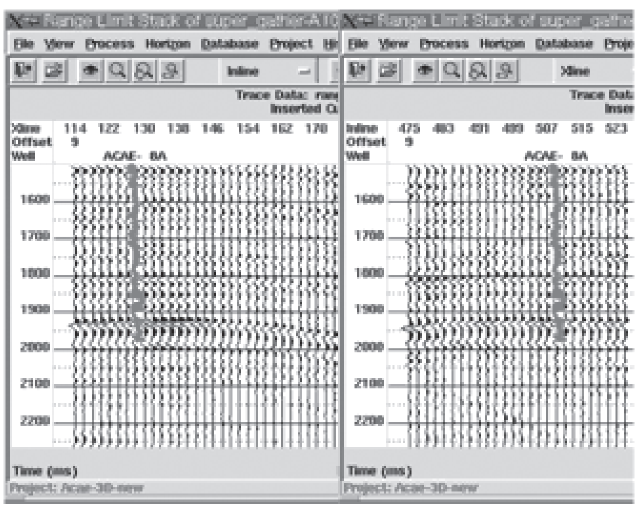

Figure 18. Shows a near angle stack (0°-18°) at well Acae-8a location with Inline 509 on the left, Xline 128 on the right

cept and B is the gradient (usually the best AVO attribute to distinguish class III AVO anomalies); scaled Poisson's ratio change (aA+bB) and scaled S-wave reflectivity (aA-bB).

Fluid seismic evaluation using real traces

Seismic data used in this analysis includes the super-gather generation to increase the effective signal to noise ratio, an angle-gather to find the effective angles at the reservoir time (0°-36°), and finally a range limited stacks to create a near angle stack (0°-18°) and a far angle stack (18°-36°) to detect amplitude anomalies. The near and far limited stacks corresponding to the Acae-10 and Acae-8a locations are shown in figures 16 through 19.

Comparing the near-angle against the far-angle stack for wells Acae-10 and Acae-8a, it is possible to notice an amplitude increment from near to far stacks in all traces. This characteristic (positive intercept and positive gradient) allows for the classifying of this AVO behavior in the first quadrant of the classification of AVO responses, as proposed by Castagna and Swan in 1997. In the first quadrant, reflections are interpreted as not being anomalous (Castagna and Swan, 1997). In summary, the reservoir fluid in the Caballos formation does not contribute substantially to the seismic signature in the predominant frequency of the seismic data.

CONCLUSIONS

- With the combination of the geophysical techniques applied in this study and the seismic data available, it was possible to map rock properties (such as porosity and poisson's ratio) calculated at laboratory scale to the large seismic scale with a fair degree of accuracy for the Caballos formation.

- The Poisson ratio and Vp/Vs ratio generated through elastic inversion identified a favorable match with the rock-physics, which allows identification of good- and low-quality reservoir rock at the Caballos formation.

- Zones with better reservoir rock quality to check prospective uses at the Acae area while using seismic attribute estimation are: 1) North-West of Acae-10 well; and, 2) North-NE of San Miguel-1 well (as shown in Figures 2 and Figure 9).

- The four operational and stratigraphic units that compose the Caballos formation do not show independent seismic signatures in the seismic data analyzed; only top and base are uniformly identified at the Acae area through the techniques used, with a seismic sample rate of 4 ms.

- The use of partial stack information (near, middle, and far stacks) as an external attribute was effective in the estimation of porosity and gamma-ray response from seismic attributes in the Acae area.

- The fluid replacement modeling, and the preliminary amplitude versus offset analysis performed, indicate that there was no substantial contribution of the fluids to the seismic signature at the predominant frequency of this seismic survey.

COMMENTS AND RECOMMENDATIONS

Having only 8-10 seismic samples to resolve the stratigraphic complexity in the study area is not favorable. More samples and statistics are needed, in order to generate a more accurate reservoir model. A first step should be to apply the seismic attribute prediction of petrophysical properties to 2 ms seismic data for the tracing of additional details. The more information from the subsurface, the more reliable predictions of basic rock properties will be for future prospects of infill well drilling.

In order to explore below the quarter wavelength resolution on target zones with at least a 2 milliseconds seismic dataset, it would be necessary to perform a pilot test with a different combination of geophysical techniques (as described in Marfurt 2000, 2001, 2003).

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